Multi-Sensor Systems: Multiplicity helps

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SET-157

Multisensor Fusion:
Advanced Methodologies and
Applications

Outline

- Introduction
- Types of sensor networks
  - Mono / multi type sensor networks
- Radar networks
  - Some properties of multistatic radar networks
- Examples of existing multistatic radar systems

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Why Multi-Sensor Systems?

- Single sensor networks are beginning to reach their limits an sensitivity
  - Transmit power and aperture size is a limiting factor
  - Monostatic systems are vulnerable against physical and e.m. jamming
  - Stealth technology even exacerbates the sensitivity demand
- Hence sensor networks can
  - Improved sensitivity, target location, recognition and tracking
  - Counter stealth
  - Support of new processing concepts, MIMO etc
  - Reduced vulnerability to electronic and physical attack
  - Improved information content

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Why Multi-Sensor Systems?

- Multi sensor systems offers new possibilities for detecting, tracking, and classification of targets
- Systems designs have the potential for the target to be ‘inside’ the system
- This may lead to a radical new form of single sensor type networks and also to new processing challenges such as near field operation

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Classification of Sensor Networks

- Multi-type sensor networks
  - More information about the target helps to classify
  - Co-located sensors
  - Data fusion in a central processing stage (only target / tracks can be fused)
- Mono-type sensor networks
  - higher resolution
  - better parameter identifiability due to joint estimation
  - Bistatic constellations
    - interference and jamming suppression
    - fading migration
  - Decentralised processing

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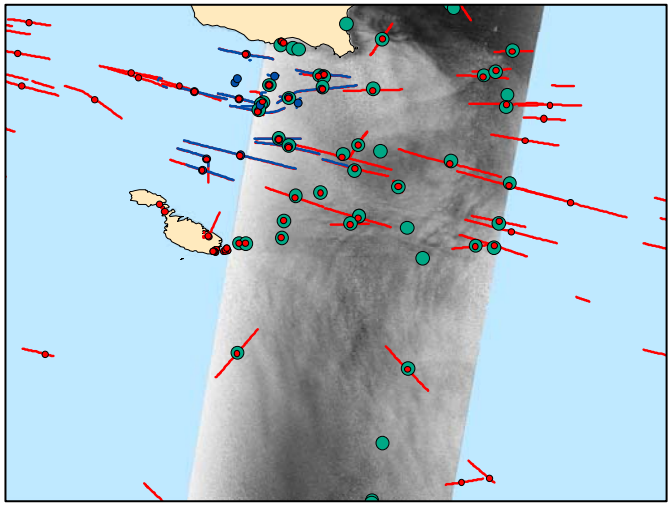
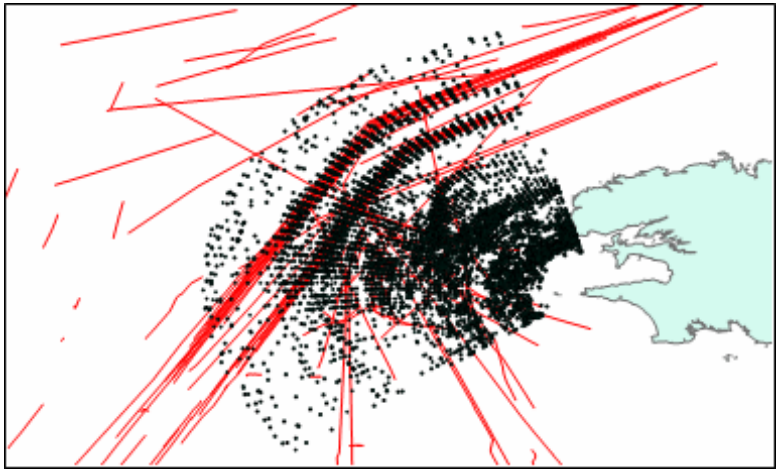
Example for Multi-Type Sensor Network



Integration of ship-based AIS tracks, ship-based radar tracks, and satellite imagery-based ship detections



AIS data and experimental HF radar ship-detection data

Courtesy by NURC

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Mono-Type Sensor Network

- Advantage
  - Node can be transmitter, receiver, or both a transmitter and a receiver
  - Transmit node can be designed to optimze the system performance: carrier frequency, pulse length, power of pulse, pulse bandwidth, PRF, type of modulation, and polarisation of transmission

- Multiple monostatic operation
- Multiple bistatic operation
- Mulstatic operation (MIMO)

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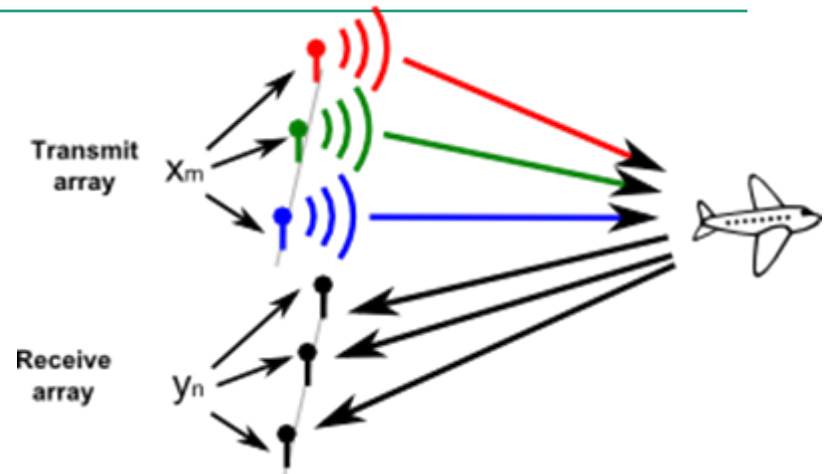
Mono-Type Sensor Network

- **Co-located sensors**
  - Omnidirectional space illumination
  - Reduced coherent energy on target
  - All the benefits of coherent beams obtained post-processing



- **Distributed sensors**
  - Extended target acts as channel with spatial selectivity – target cross section (RCS) diversity
  - High angle resolution localization
  - Multiplicity of sensors supports high accuracy localization
  - Handling of multiple targets
  - Improved Doppler processing through diversity of look angles and mitigation of the problem of low radial velocities

➢ **Decrease number of elements in sensor array**

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Which Sensor?

- Sensors should operate independent of :
  - daytime
  - weather (fog, rain, clouds, sandstorms, …)
- For surveillance applications the sensors working range is up to several thousands of kilometres.
- Radar / Sonar are ideal sensors for surveillance and reconnaissance applications

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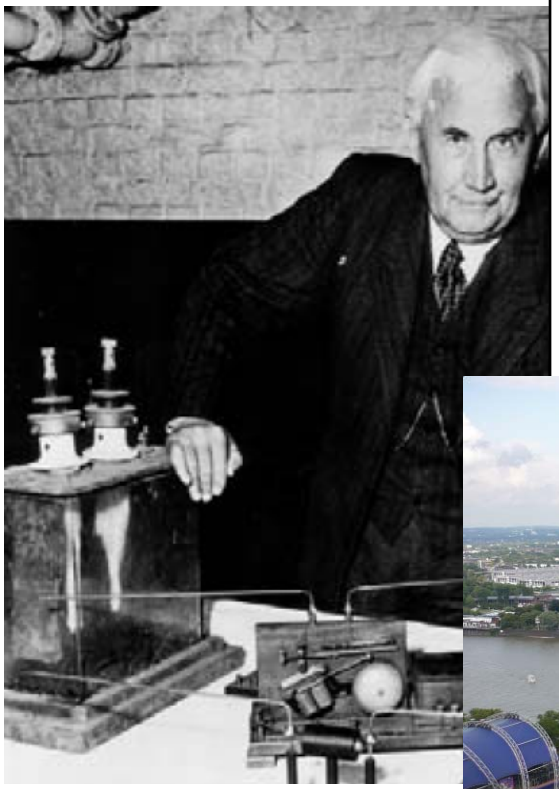
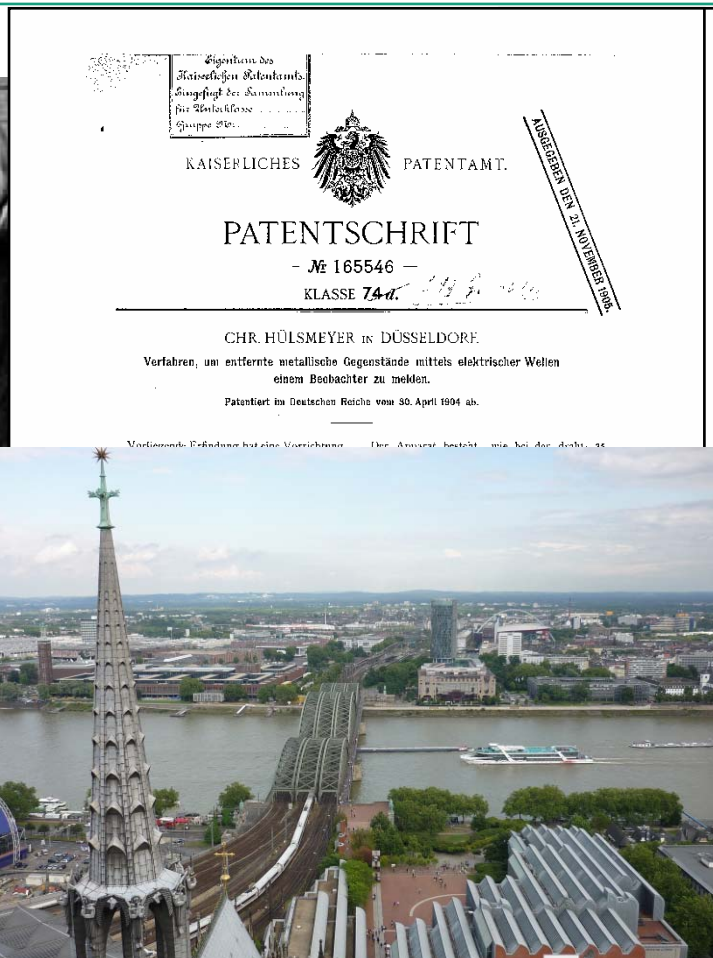
First Radar Experiments was Bistatic

- 1904 -



Christian Hülsmeyer



Eigentum des Kaiserlichen Patentamts. Eingefügt der Sammlung für Verkehrswesen ..... Gruppe 80c.

KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 21. NOVEMBER 1905.

PATENTSCHRIFT

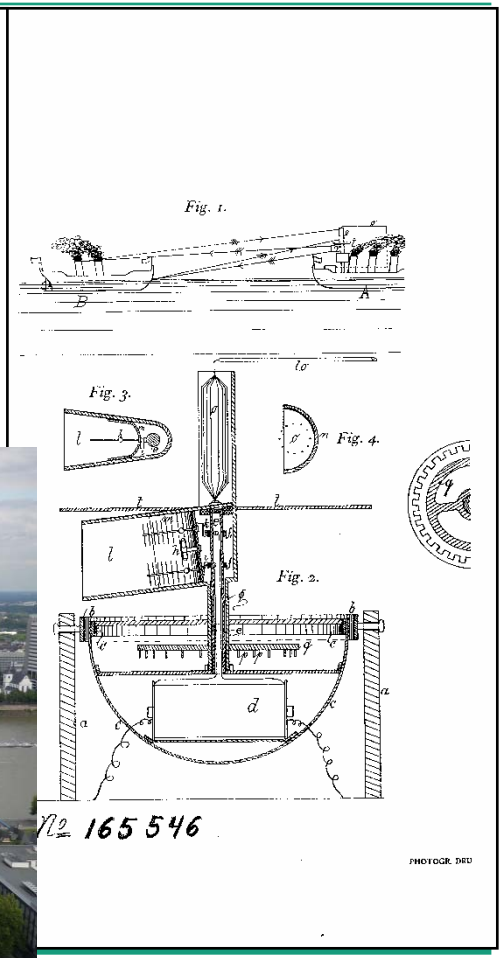
– № 165546 –

KLASSE 74 d.

CHR. HÜLSMEYER IN DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

Patentiert im Deutschen Reiche vom 30. April 1904 ab.



Cologne – Hohenzollern bridge

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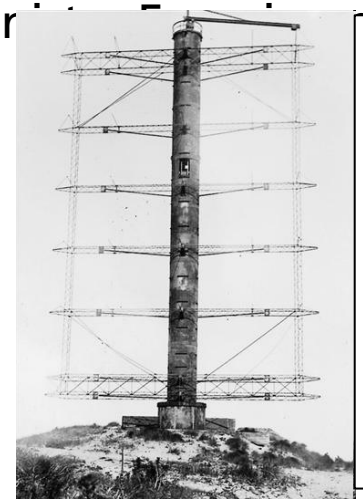
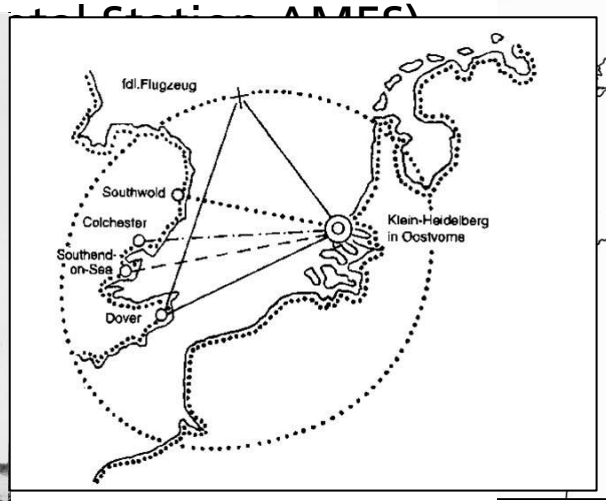
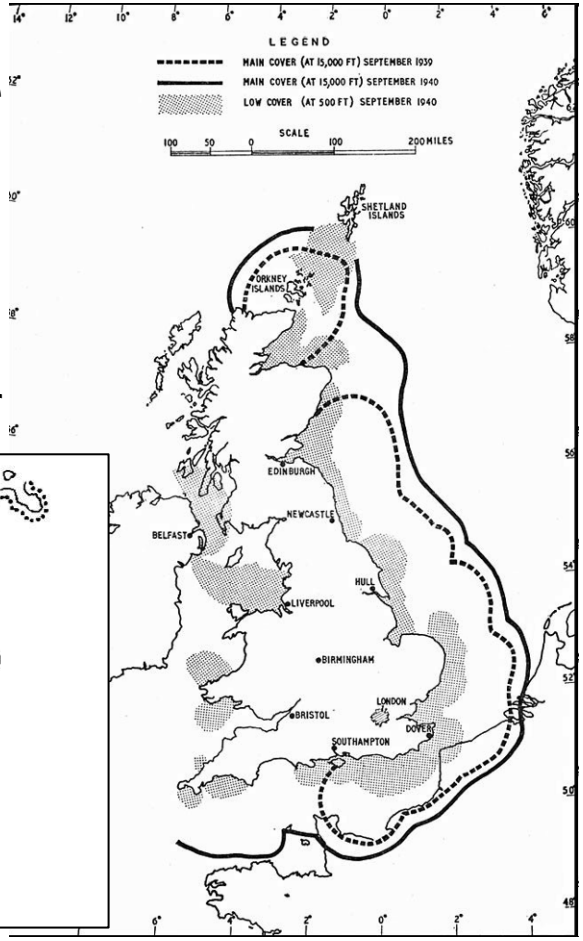
Bistatic Radar Rediscovery

- during WW II (1942/43) -

- Klein Heidelberg (KH) was a code name for a passive receiver of a bistatic hitchhiker system, (Dipl. Wächter / Telefunken) which exploited the transmissions from the British Chain Home (CH) radar stations.
- Chain Home was a ring of costal early warning radar stations (Air Mi
- CH was designed for long range (=> not able to detect low flying aircrafts)
- 6..25 us (Δr=1.8km)
- 350kw/750kW/1MW







Neale, B.T., 'Chain Home – the First Operational Radar', *GEC Journal of Research*, Vol. 3 No.2 pp73-83, 1985.

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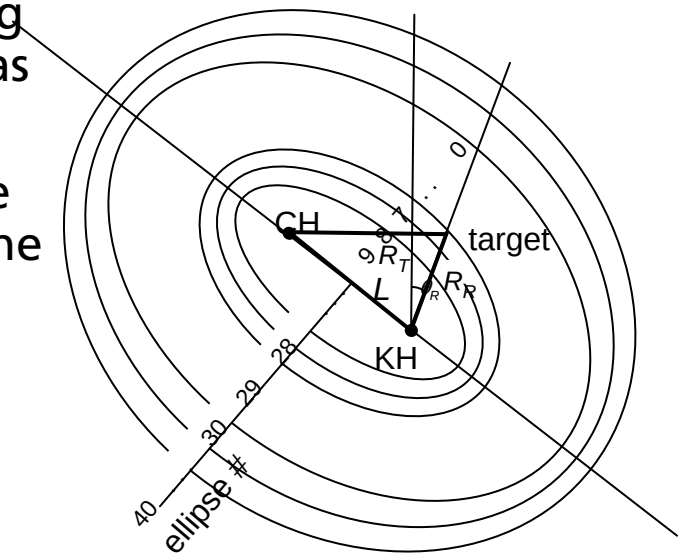
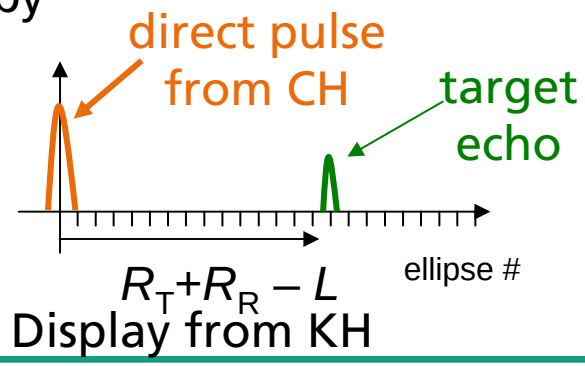
http://www.gyges.dk/Klein%20Heidelberg.htm

Klein Heidelberg and Chain Home

- The pulse and the reflection of an aircraft having been hit by the same pulse from a CH station was displayed on the range scope.
- The range to the CH station was known, and the length travelled by the reflected pulse defines the eccentricity in an ellipse whose foci are the CH station and the KH station, the position of the aircraft is thus the cut between the ellipse and the bearing to the aircraft.
- Direction of echo was determined by comparing the relative strength of the echoes picked up by different crossed dipoles.

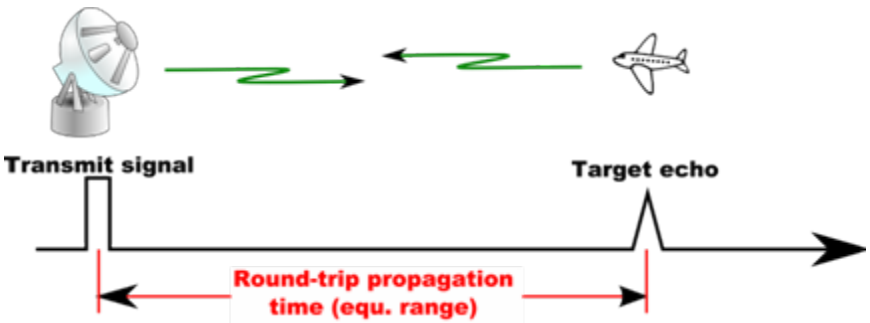




Radar

- RAdio Detection And Ranging -

- In its simplest form, the radar problem is: transmitting a waveform *s(t), which is* known to the receiver, and observing a time-delayed echo signal *r(t)*



$$r(t) = s(t-\tau) + \text{noise}$$

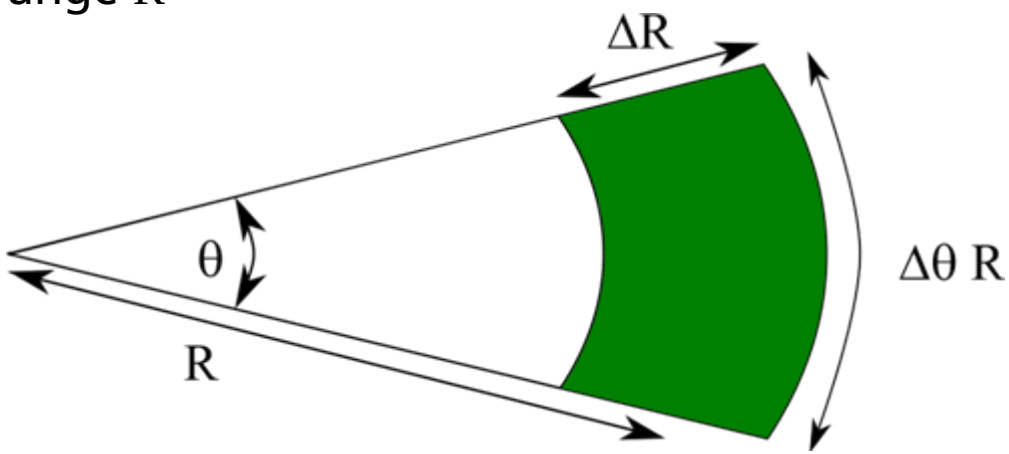
- detect the presence of a target
- estimate the target range r_0 from the time delay $\tau = 2r_0 / c$
- If target moves towards radar Doppler shift occurs: $f_d = -\frac{2v_0}{c} f_0$

$$r(t) = s(t-\tau)\, e^{j2\pi f_d (t-\tau)} + \text{noise}$$

Radar – Resolution

- monostatic setup -

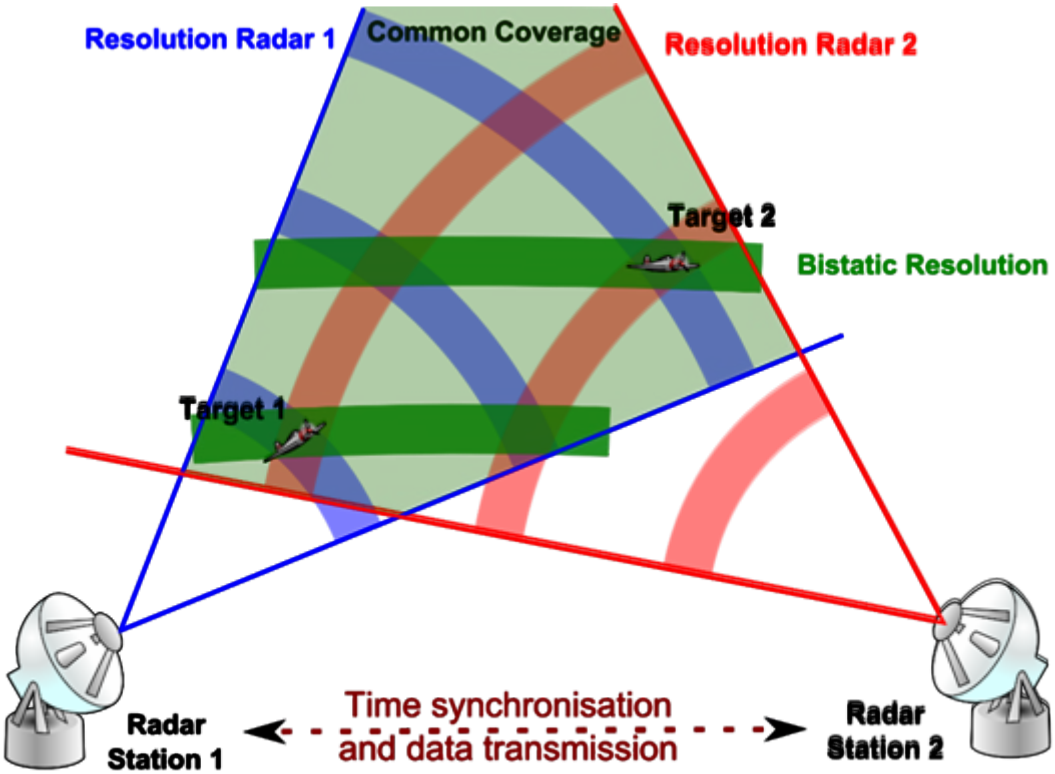
- Target localization in a resolution cell
  - range resolution is proportional 1/(signal bandwidth)
  - cross range resolution is proportional antenna beamwidth and range R



- The cross range resolution is limited by antenna size, and will degrade with range. Generally cross range resolution will be much poorer than down range resolution.

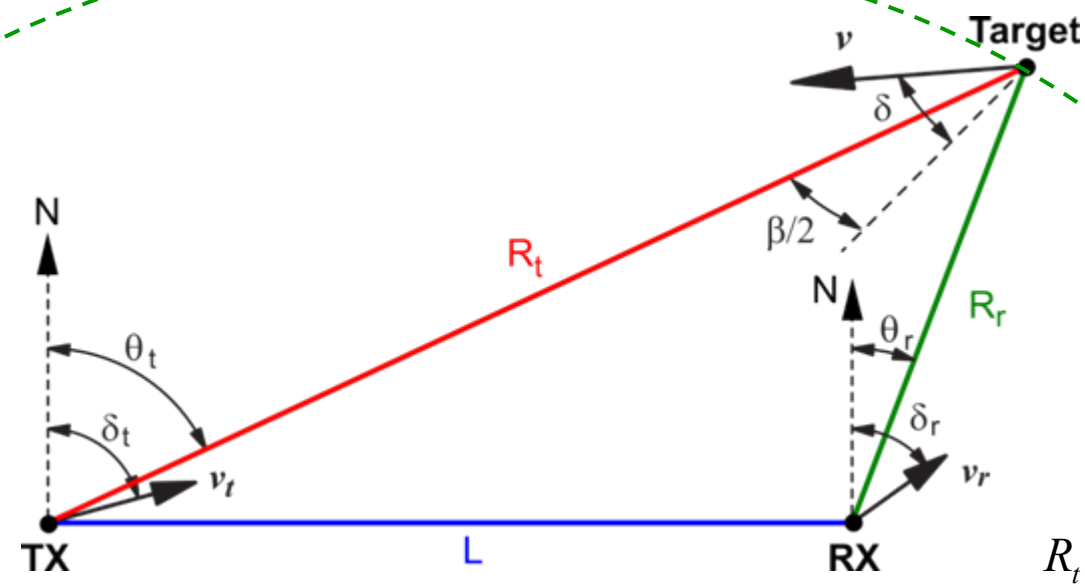
Radar resolution

- multistatic setup -



- Single receiver shows good detection performance, but limited localization capability
- Multistatic systems enhances detection robustness and localization accuracy.

Bistatic geometry



$$R_t + R_r = \text{const.}$$

- Contours of constant bistatic range are ellipses, with the transmitter and receiver as the two foci
- Targets lying on the transmitter-receiver baseline have zero bistatic range.

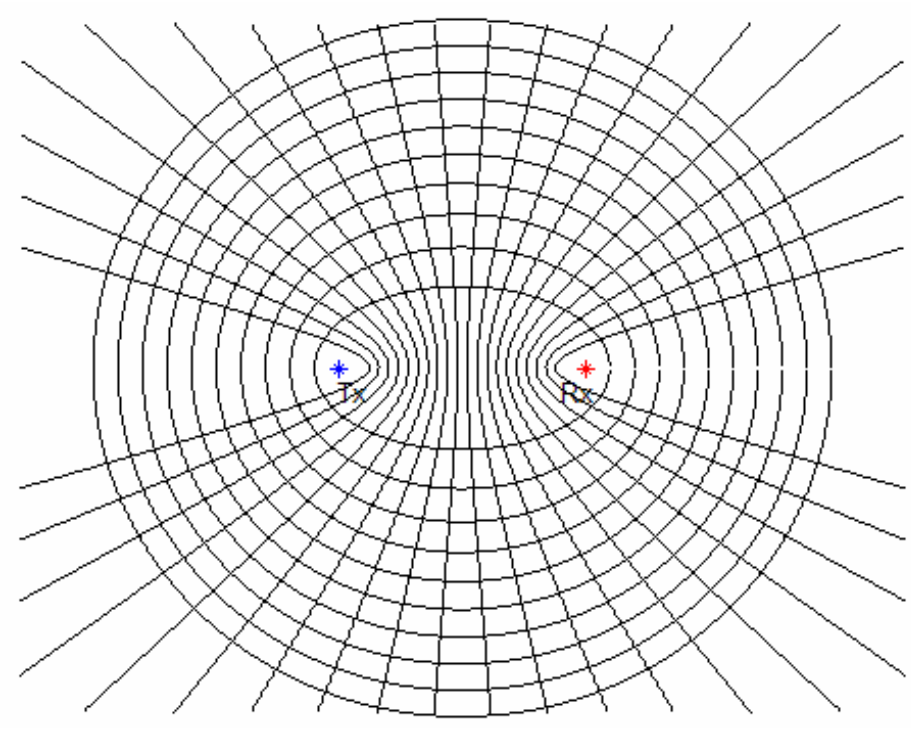
Ellipses and hyperbolas

- Ellipse eccentricity

$$e = \frac{L}{R_t + R_r} = \frac{L}{R}$$

$$e = 0 \ldots 1$$

- Concentric hyperbolas
  - $(R_t - R_r)$ = const
  - TDOA (ESM)
    - multilateration

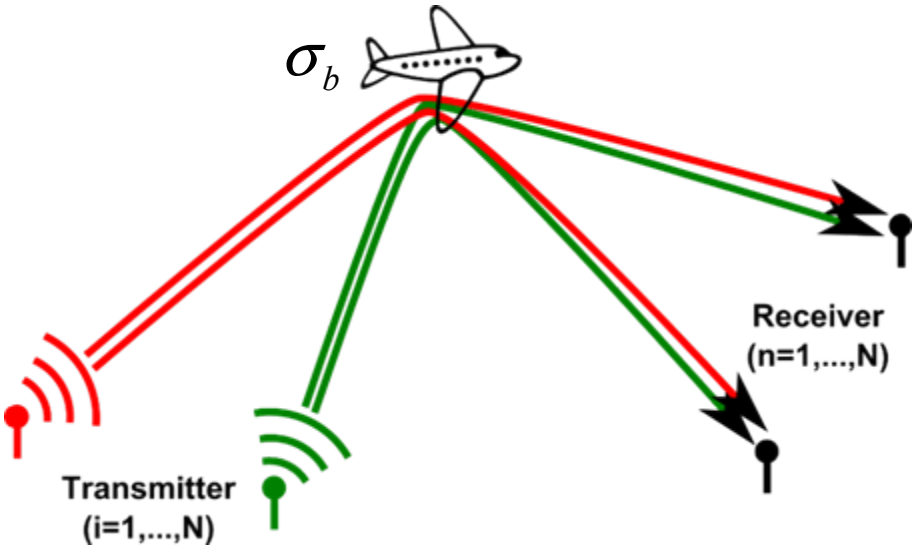


e={0.83,…,0.33}

The multistatic radar equation

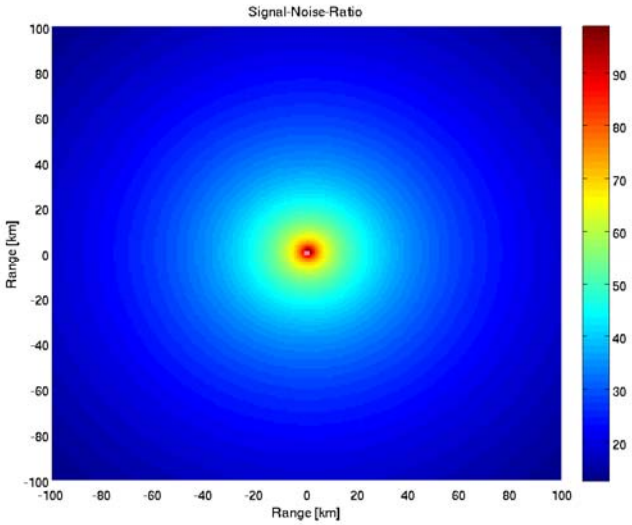
- This is derived in the same way as the monostatic radar equation :

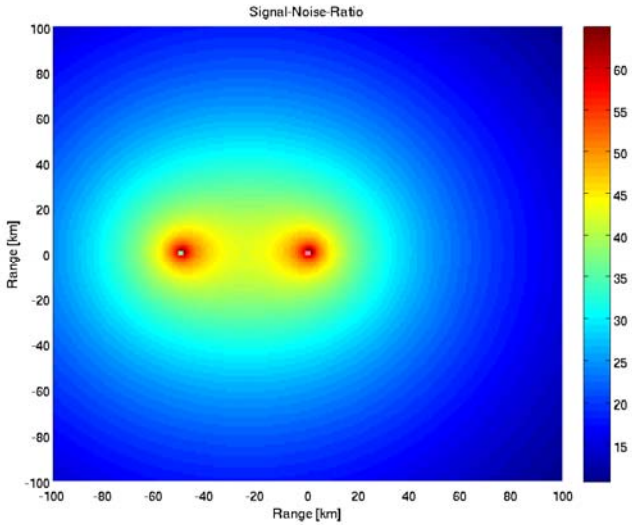
P_T	Transmitted power
G	Antenna gain
λ	Carrier wavelength
F	Pattern propagation factor
σ_b	Target RCS
k	Boltzman constant
T_0	Noise temperature
B	Noise bandwidth in receiver
L	All other losses

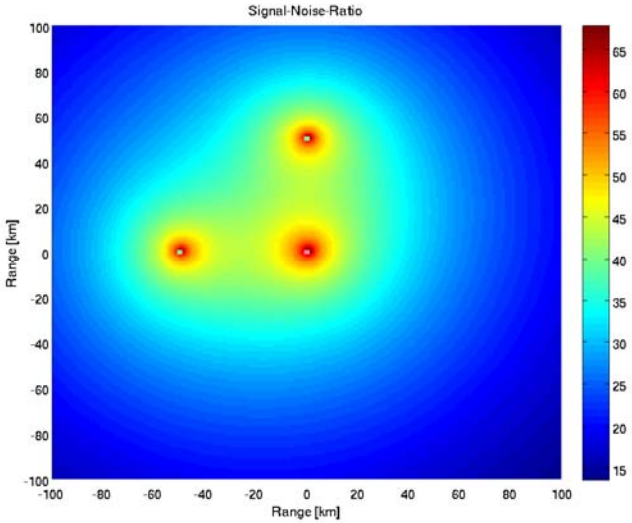


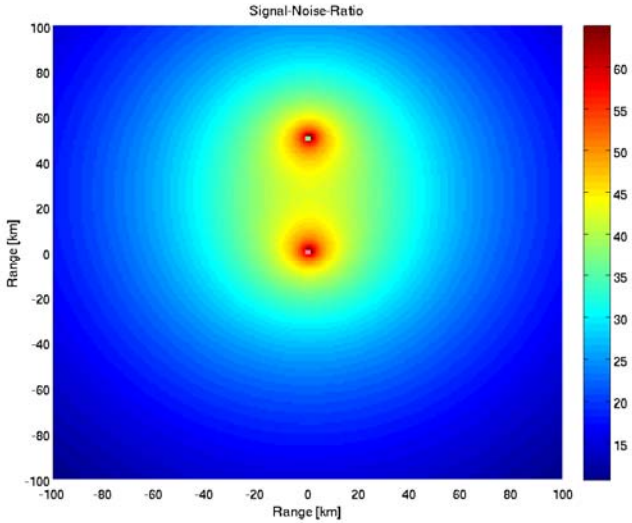
$$\frac{P_r}{P_n} = \sum_{i=1}^{N} \sum_{n=1}^{M} \frac{P_t G_{tx}(i) G_{rx}(n) \sigma_b \lambda^2}{(4\pi)^3 k T_0 B F R_{tx}^2(i) R_{rx}^2(n) L}$$

SNR for mono-, bi-, and multistatic radar









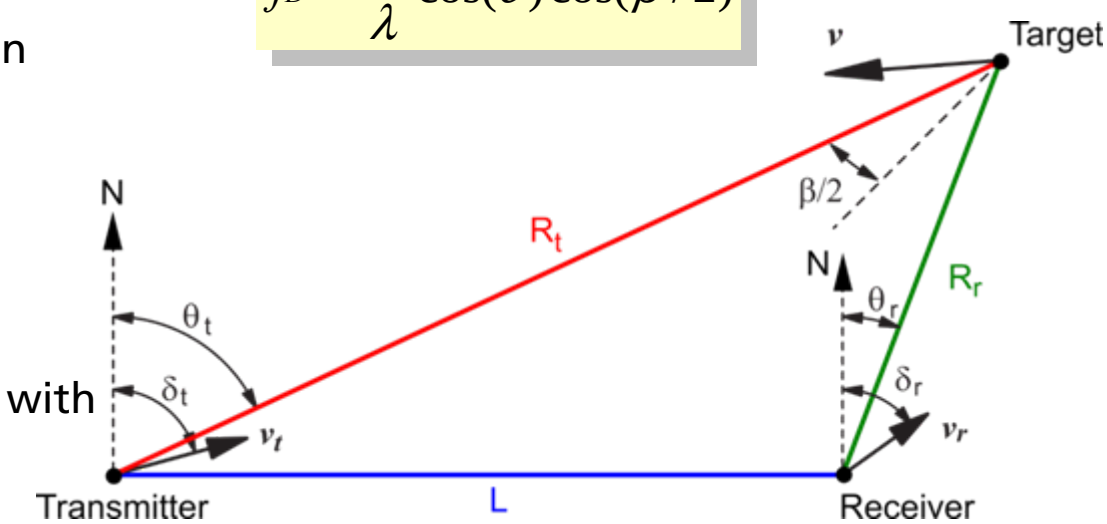
Bistatic Doppler

- Bistatic plane spanned by TX, RX and Target

$$f_D = \frac{1}{\lambda}\left[\frac{\delta}{\delta t}(R_t + R_r)\right] = \frac{1}{\lambda}\left[\frac{\delta R_t}{\delta t} + \frac{\delta R_r}{\delta t}\right]$$

$$f_D = \frac{2v}{\lambda}\cos(\delta)\cos(\beta/2)$$

L	Baseline
R_t, R_r	Bistatic range
v	Target velocity component in bistatic plane
β	Bistatic angle
$\beta/2$	Bistatic half sector
δ	Angle of the target velocity with respect to the bisector



$$\beta = \theta_T - \theta_R$$

M.C. Jackson, 'The geometry of bistatic radar systems'; *IEE Proc.*, Vol.133, Pt.F, No.7, pp604-612, December 1986.

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Bistatic Doppler

δ	β	f_D	condition
–	0°	$(2v/\lambda)\cos\delta$	monostatic
0	0°	$(2v/\lambda)$	monostatic
–	180°	0	forward scatter
± 90	_	0	$v \perp$ bisector
$\pm\beta/2$	_	$(2v/\lambda)\cos^2(\beta/2)$	$v \parallel$ TX or RX
0,180	_	$\pm(2v/\lambda)\cos(\beta/2)$	$v \parallel$ bisector
$90 \pm \beta/2$	_	$\mp(2v/\lambda)\sin\beta$	$v \perp$ TX or RX LOS

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Summary of properties

- There is a co-ordinate distortion effect; targets on the transmitter-receiver baseline have zero bistatic range. Elsewhere, contours of constant bistatic range are ellipses with the transmitter and receiver sites as the two foci. *The distortion can be corrected with a knowledge of the bistatic geometry.*

- Similarly, contours of zero Doppler are the same ellipses of constant bistatic range. *Contours of maximum Doppler are hyperbolae crossing the ellipses orthogonally.* Moving targets cannot present zero Doppler to two receiving sites simultaneously.

- There are several configurations of transmitters and receivers. Azimuthal discrimination (i.e. directional antennas) at both transmitter and receiver is desirable, since otherwise the system is vulnerable to responses from sidelobes. A directional receive antenna must scan at a non-uniform rate, which practically rules out mechanical scanning. The form of scanning required follows the position of the RF pulse through space, and is known as pulse chasing. Thus, either a small number of electronically agile beams or a static set of contiguous beams will be required. Such a receiving system is unlikely to be either simple or cheap, but because the receiver is passive it is much less vulnerable to attack.

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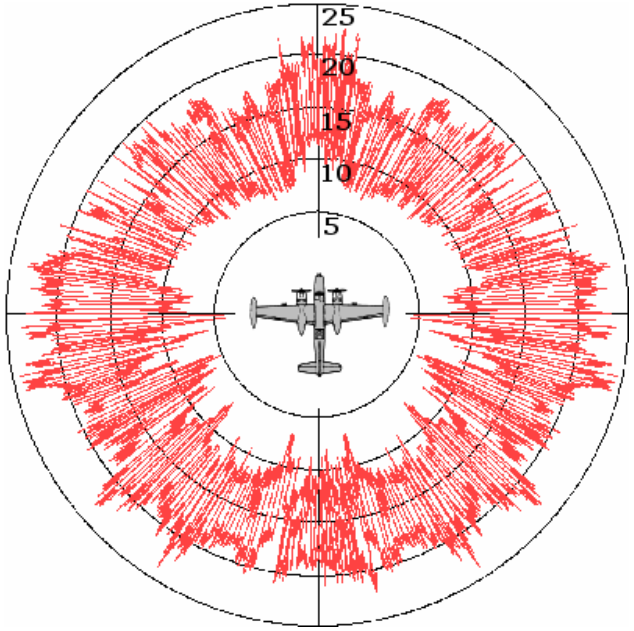
Multistatic RCS

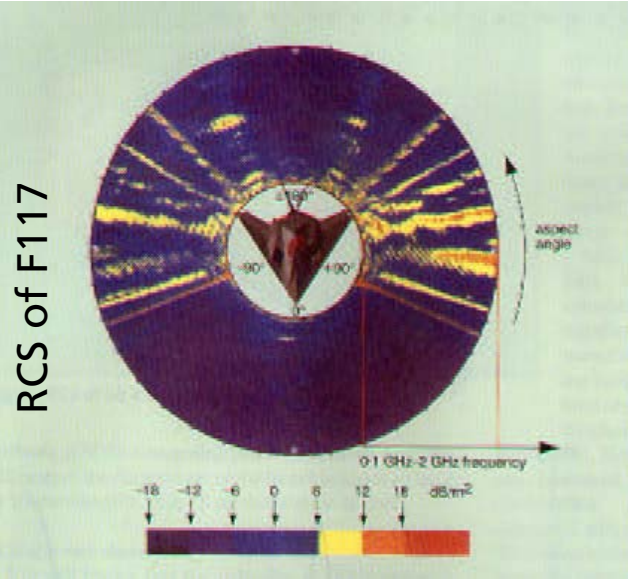
- The radar cross-section σ_b is for a bi-/multistatic configuration not the same as for a monostatic, although the range of values of σ_b for a particular (non-stealthy) target will be comparable with the range of values of monostatic cross section. Thus a particular target is unlikely to present a low cross section to more than one transmitter-target-receiver geometry. Additionally, at large angles target glint is drastically reduced, eliminating this contribution to radar inaccuracies.



Multistatic RCS

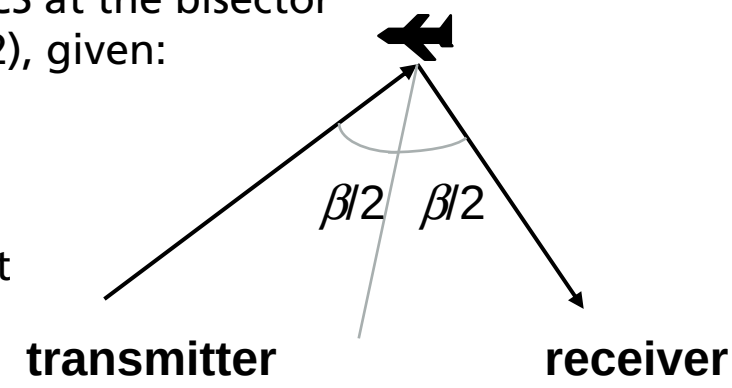
- Stealthy targets are designed to have a low monostatic cross section, partly by shaping so as to scatter energy in directions other than the monostatic direction. Hence, the multistatic radar cross section of stealthy targets may be larger.

- Receiving or transmitting stations can be used interferometrically to obtain high azimuthal discrimination
- Sources of interference can be located by triangulation
- Passive detection (correlation) techniques can be employed to locate noise-like interference sources.

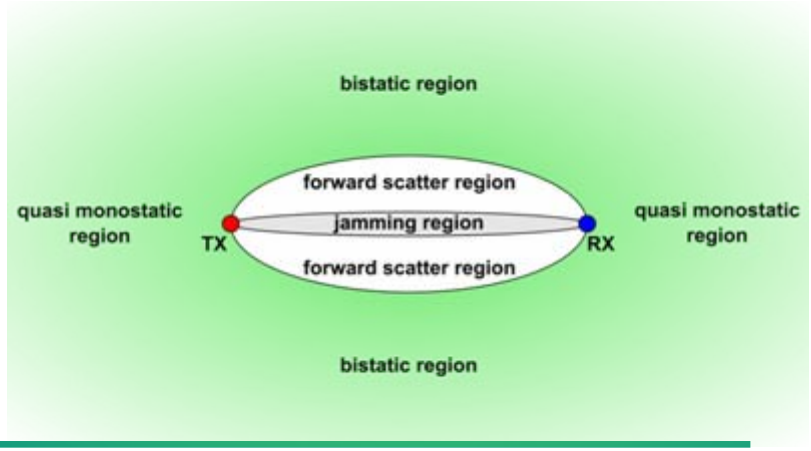


Multistatic RCS

- The bi-/multistatic RCS is equal to the monostatic RCS at the bisector of the bistatic angle β, reduced by the factor cos(β/2), given:
  - sufficiently smooth targets
  - no shadowing
  - retroreflectors (trihedal – cat's eye) persist



- Three multistatic RCS phenomena that may be exploited as a counter to stealth aircraft have been identified:
  - resonance scatter
  - forward scatter
  - specular reflection



- Resonance scatter and specular reflection apply also to monostatic radar; forward scatter applies only to bistatic radar

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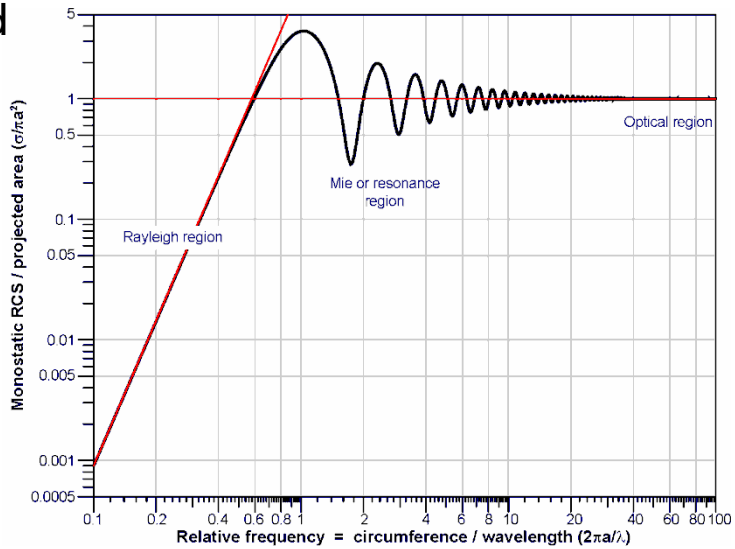
Multistatic RCS

- Resonance scatter -

- The resonance scatter effect for monostatic radars is well known for conventional (non-stealth) targets. In the simplest case of a conducting sphere of radius a, resonance occurs in the region: $0.5 < 2\pi a / \lambda < 10$

- "Physically, the resonant region can be explained by the interference between the incident wave and the creeping wave, which circles the sphere and either adds to or subtracts from the total field at the leading surface" (Barton)
- The net result of these additive effects is that when wavelengths are of the order of discrete aircraft dimensions, for example fuselage, wing, tail, inlet and exhaust ducts, the resulting resonance significantly enhances RCS when compared to the optical region, which for the sphere starts at: $2\pi a / \lambda > 10$



Radar cross section of a perfectly conducting sphere
- adapted from Blake, 1972, NTIS document AD 704746 -

Multistatic RCS

- forward scatter -

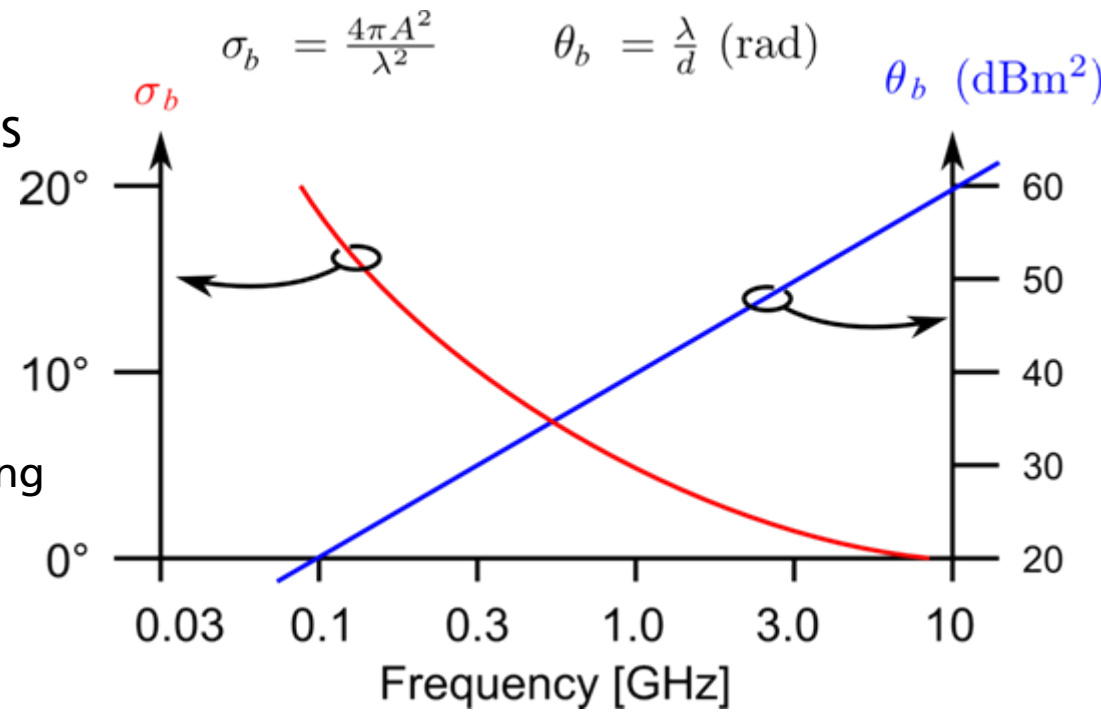
- A target on the transmitter-receiver baseline, even if it is completely stealthy, will scatter a significant amount of energy - in fact the RCS will be of the order of

$$\sigma_b = 4\pi A^2 / \lambda^2$$

- The angular width of the scattering will be of the order of

$$\lambda / d \quad \text{[radians]}$$

which tends to favour a low frequency.



- Forward scatter is good for target detection, location and tracking difficult as no range and Doppler information .

Multistatic RCS

- Specular reflection -

- A third counter-stealth capability has sometimes been ascribed to bistatic radars in general: the ability to detect specular reflections that have purposely been directed away from anticipated monostatic radar threat locations, for example by using tilted surfaces or facets on stealth platforms.

- The assertion is that carefully selected location of multiple receivers, these off-normal speculars of large amplitude can be detected and tracked or networked together to support some level of engagement.

- This requires rather specific geometries, and the flashes will be of short duration, so at this time it would appear optimistic to ascribe more than a fence-type alerting and coarse cueing capability when exploiting specular reflections from stealth aircraft.

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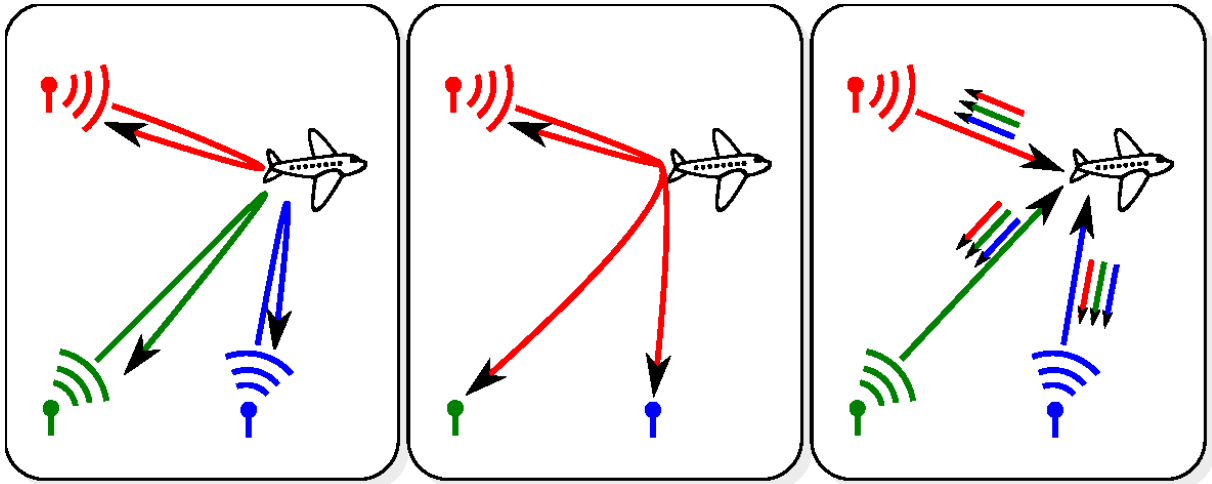
Types of multistatic radar networks

Modes of operation:

- Monostatic operation,
- Bistatic operation,
- Any combination of the first two categories

Type of network:

- Coherent networks,
- Short term coherent networks,
- Incoherent networks.



Location of nodes:

- Co-located / distributed
- Fixed / mobile nodes
- Ground based / airborne / space-based / hybrid sensor network

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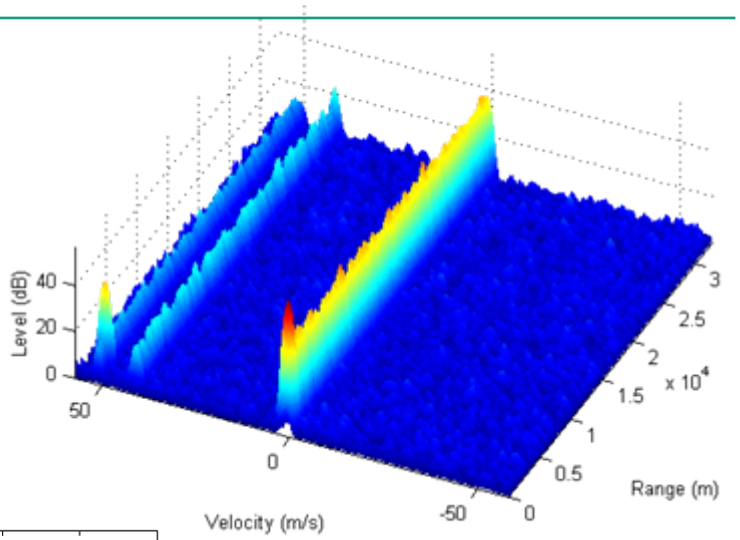
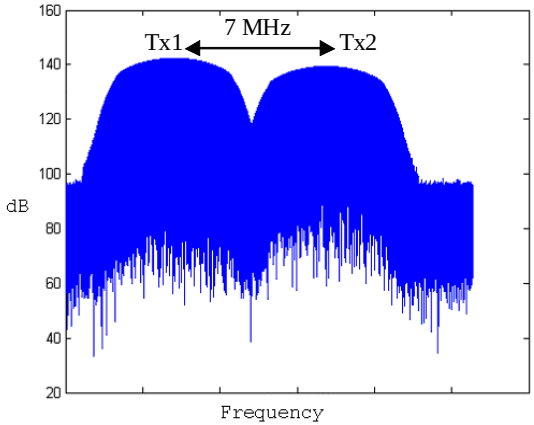
Types of multistatic radar networks

- A further distinction of multi radar networks is possible by their ability to distinguish signals using either:
- Time separation,
- Frequency separation,
- Code diversity,
- Many processing options





Examples of multistatic radar systems

- Massachusetts Institute of Technology's Netted Radar System (USA)
- GAMMA - GSM-Radar by Fraunhofer-FKIE (D)
- Passive Radar using DVB-SFN by Thales (F)
- Jindalee Operational Radar Network (JORN) (AU)
- Norwegian Defence Research Establishment's Experimental Bi-Multistatic CW Radar (N)
- SAIC's Passive, Multi-Static Radar System (USA)
- University College London's NetRad System (UK)
- Xidian University's Coast-ship Bi/multistatic Ground-wave Over-the-horizon Radar (CN)
- Vera and BORAP by ERA (Czech Republic)
- Wifi based passive Radar by Uni. Sapienza, Roma (I)
- Several bi-/multistatic experiments at Fraunhofer-FHR (D)
    - PETRA (passive coherent location radar) – FHR (D)
    - CORA (traffic passive radar surveillance) – FHR (D)
    - Bistatic SAR (Hybrid bistatic experiment TerraSAR-X – PAMIR)
    - Marauder's Map – Wifi Radar network fur surveillance applications – FHR (D)

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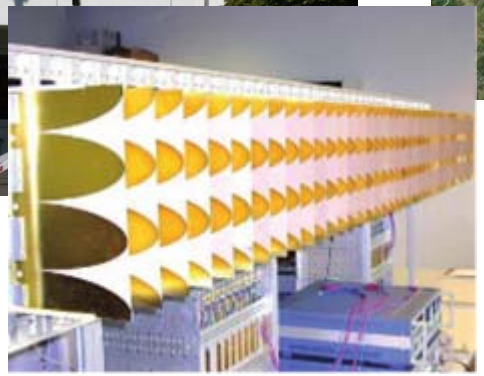
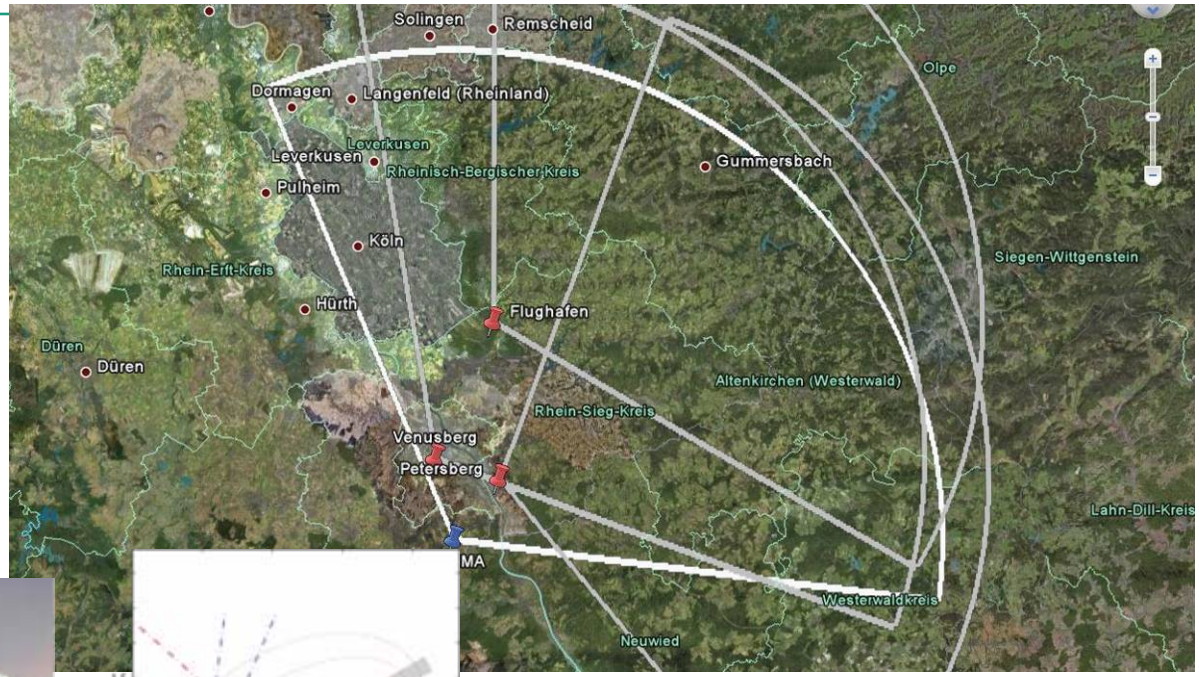
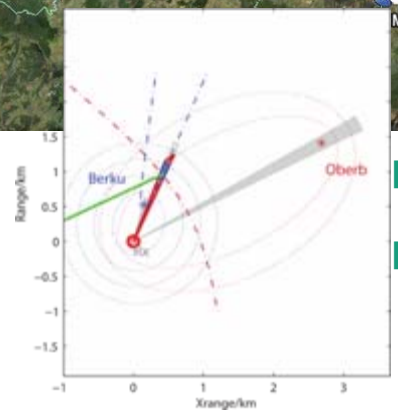
Gamma
by Fraunhofer-FKIE, D







- GSM base stations (1.8 GHz)
- Digital antenna array consists of 32 (or 16 columns on mobile platform)

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TechSat 21

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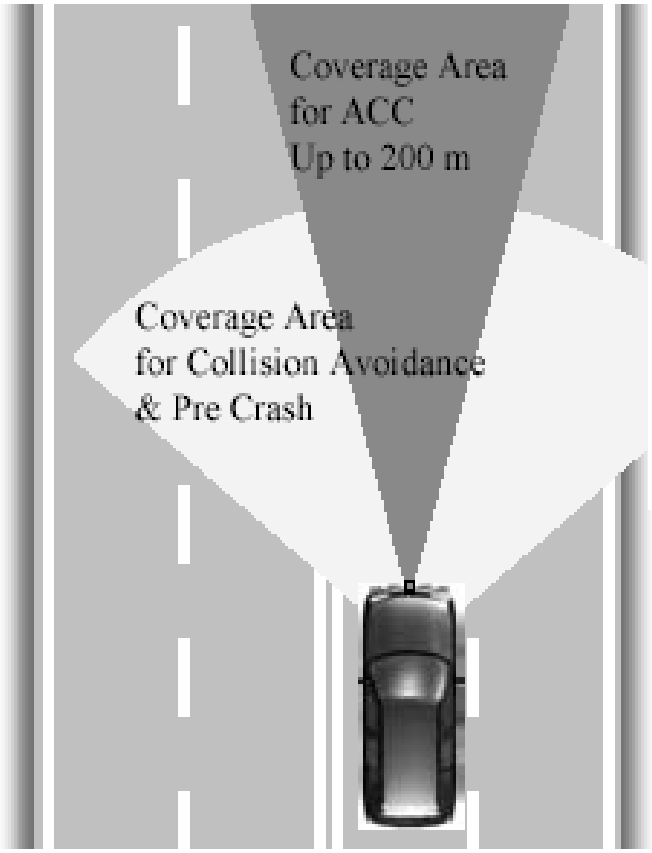
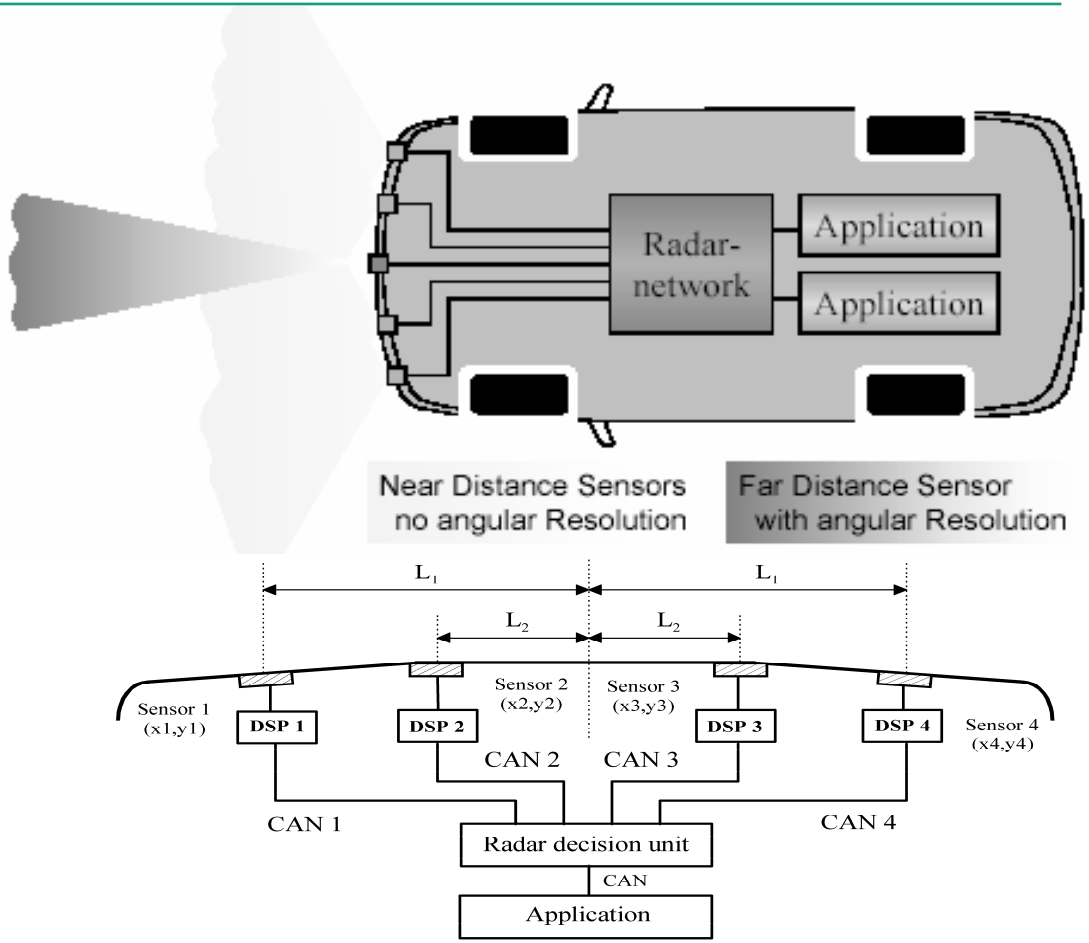
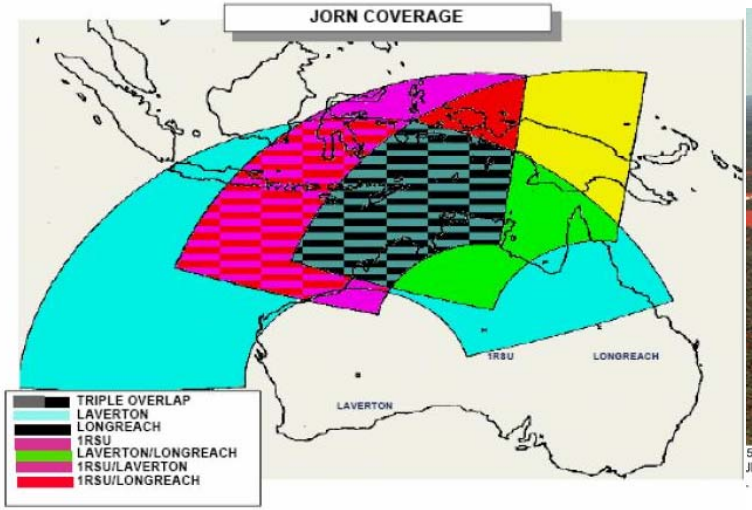
Automotive Radar Network

- by TU-Hamburg Harburg -

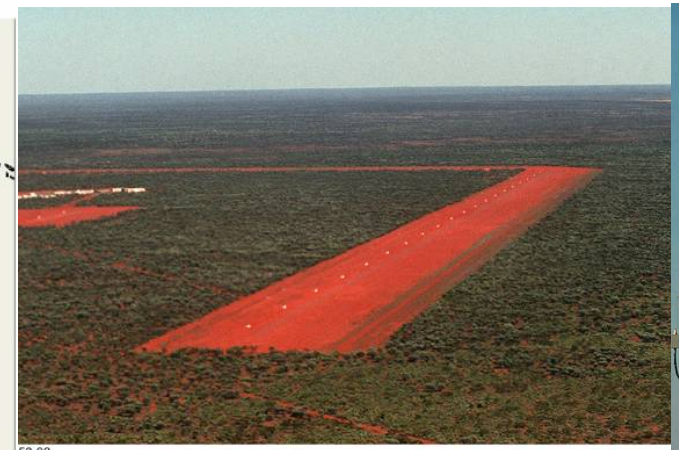




Jindalee Operational Radar Network (J.O.R.N)



Source: Jindalee Project Office



53-03
JECT RECEIVER SITE, LAVERTON W.A.
. DAVE BROOS, DEFENCE PUBLIC AFFAIRS.

CAND98/0153-25
JORN PROJECT RECEIVER SITE ANTENNA ARRAY, LAVERTON W.A.
PIC BY CPL DAVE BROOS, DEFENCE PUBLIC AFFAIRS.

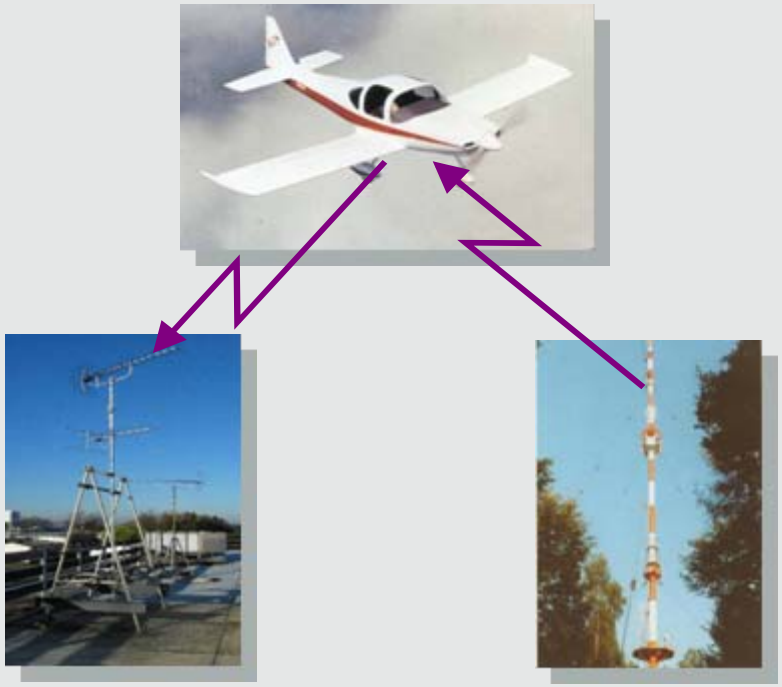
CAND98/0153-04
JORN PROJECT TRANSMITTER SITE, LAVERTON, W.A.
PHOTO BY CPL DAVE BROOS, DEFENCE PUBLIC AFFAIRS

- Over-the-horizon radar
- Surveillance area 37.000 km^2
- Official range ~3000 km (depends on atmospheric conditions up to and including Korean peninsula)

Airspace surveillance with passive radar

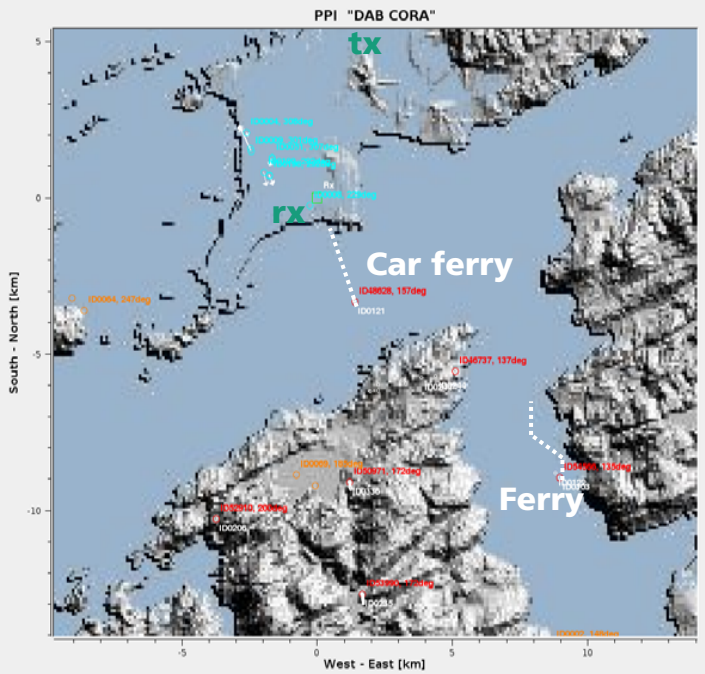
- Passive coherent location (PCL) uses illuminators of opportunity (e. g. radio and television transmitters).
- PCL reduces the vulnerability since no own e.m. power is transmitted.
- Potential to detect also low flying targets with low RCS.
- FHR operates two experimental PCL systems.
- The DAB waveform has proven to get the best results.

- Passive coherent location



FHR experimental system PETRA

Passive radar surveillance



- Using DAB (digital audio broadcast), the FHR system **CORA** can detect and locate aircrafts and even ferries at a range of more than 20 km, validated at a NATO campaign in Norway
- FHR performs research on passive radar for border protection (EU project ARGUS)

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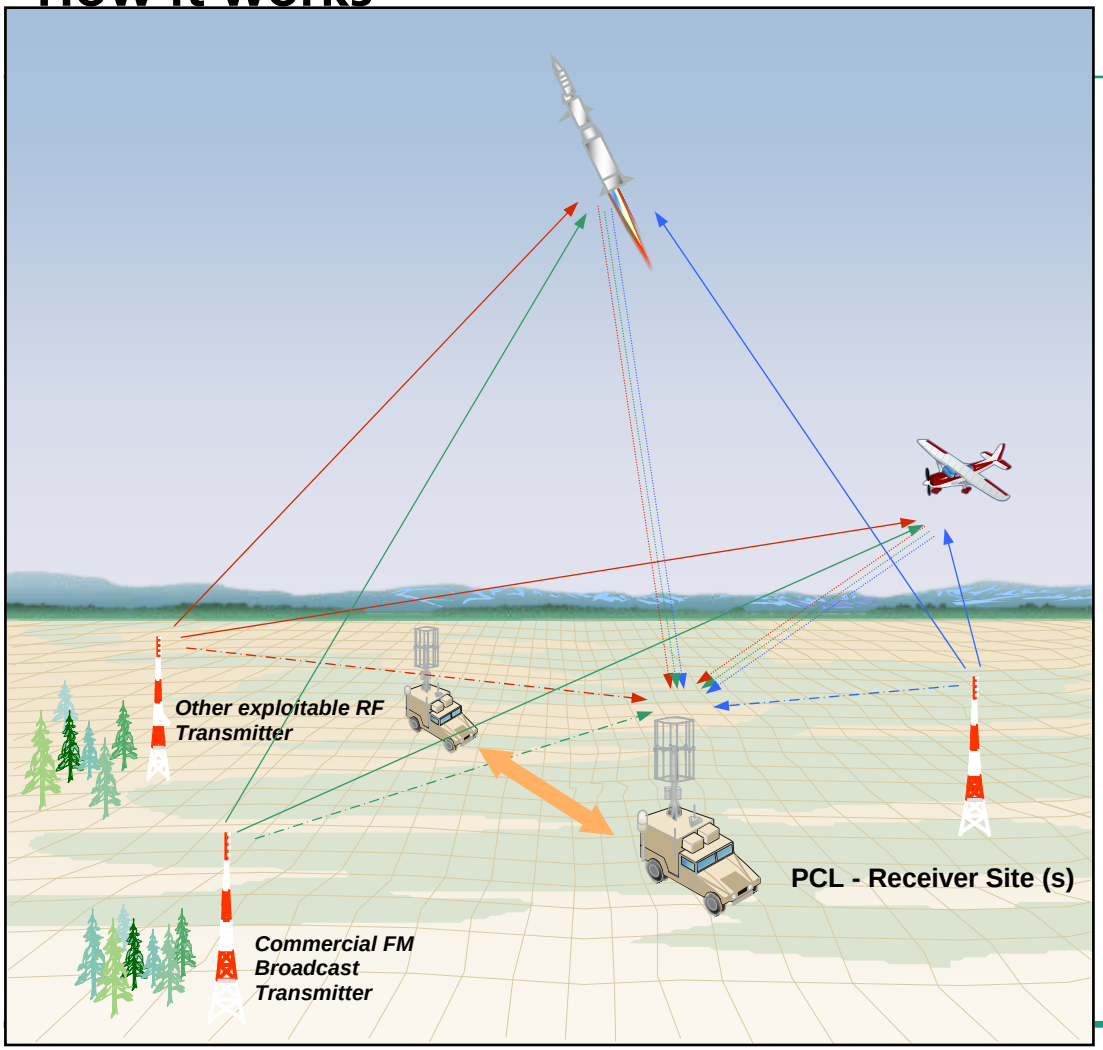
PCL – Radar (Passive Radar)

- How it works -



Legend:

Illumination — Reference — Scattered

PCL-Radar is a passive sensor that uses emissions from indigenous transmitters as its RF sources. Illuminators of opportunity are broadcast and TV stations, but can be extended to other waveforms.

Line-of-sight is necessary between receiver/ transmitters and aircraft/missiles.
A direct reference signal is also necessary at the receiver but line of sight is not required

Reflected RF energy is collected at the receiver and compared with the original reference signal to provide detection and tracking information

Track data can be sent to the track display or to a sensor fusion or command & control system

Key Features of PCL and passive Radars

- Non-intrusive
  - No radiation
  - Low power consumption
  - Allows for covert and non-provocative installation and operation
  - Significantly reduces system vulnerability
- Simple and portable
  - COTS-product based with no moving parts
  - Easy to install and transport
  - Small footprint
  - Installation on fixed or mobile platforms
  - Runs unattended and can be managed remotely

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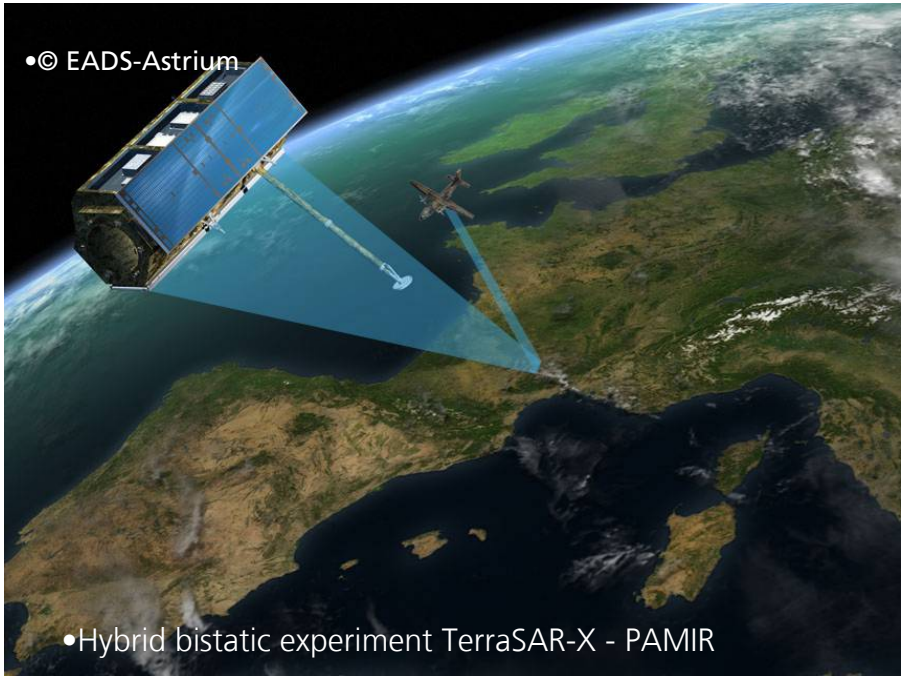
Bistatic SAR

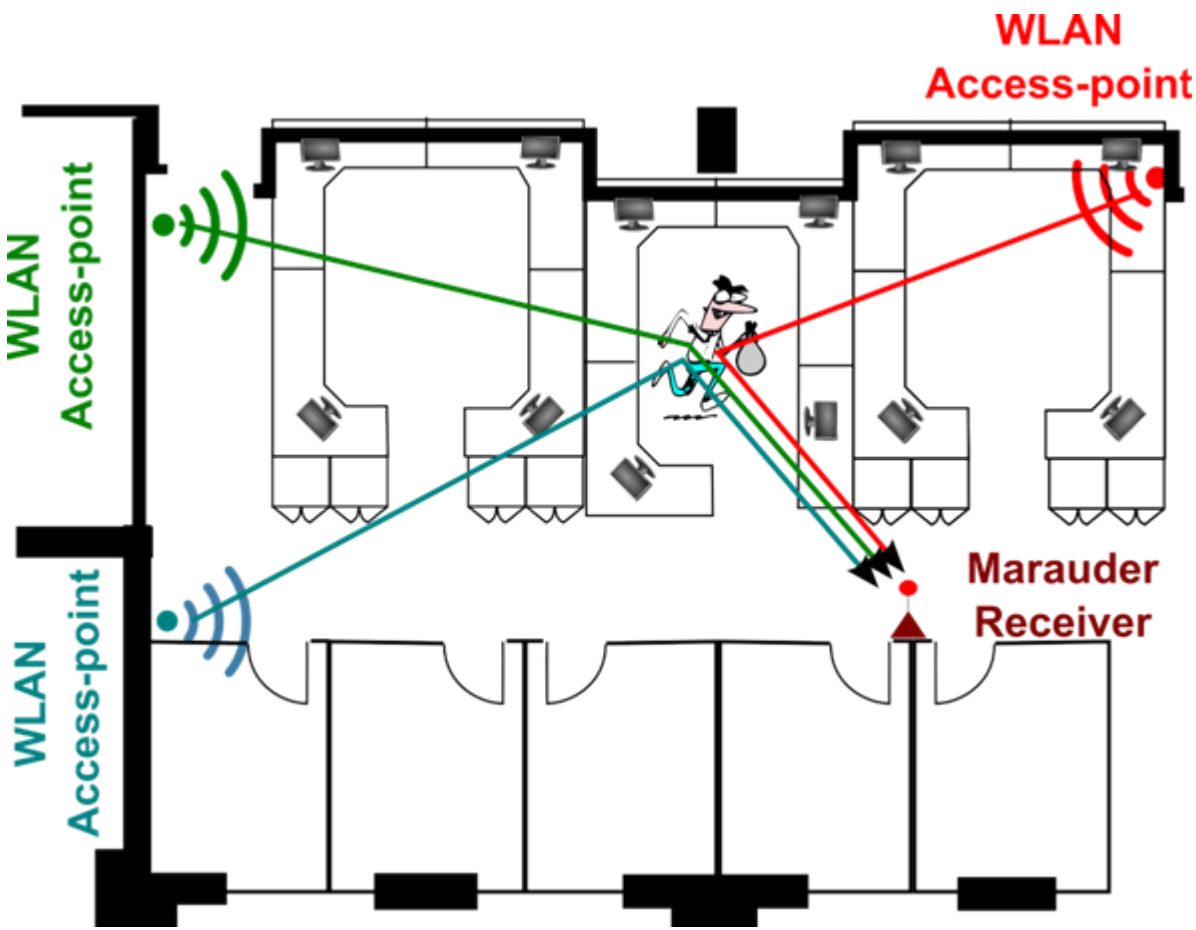


- The technique of **bistatic SAR** promises reduced vulnerability
- Experiments are conducted by FHR together with its partner ZESS (University of Siegen) under co-operation with DLR, using the **TerraSAR-X** satellite as illuminator and FHR's airborne SAR-system **PAMIR** as receiver.

Marauder's Map
- WLAN signals for passive surveillance radars -

- Wireless LAN transmissions sources might potentially act as an ideal illuminator of opportunity for short range surveillance using the PBR principle.

- Specification of signal
  IEEE 802.11 - WiFi



Thank you!
Q&A
Any questions?